WG4: SRF Linac Driven Subcritical Core

Accelerator Design Requirements for Driven Systems

Transmutation Mission

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The EUROTRANS projet

EURopean research program for the TRANSmutation of high level nuclear waste in an Accelerator Driven System

Main GOALS of the EUROTRANS program

- Advanced design of a 50-100 MWth eXperimental facility demonstrating the technical feasibility of Transmutation in an ADS **(XT-ADS/MYRRHA, short-term realisation)**

- Generic conceptual design (several 100 MWth) of a European Facility for Industrial Transmutation **(EFIT, long-term realisation)**

Transmutation Demonstration

1. MYRRHA/XT-ADS (ADS prototype)

Goals:

- **Demonstrate the concept** (coupling of accelerator + spallation target + reactor),
- **Demonstrate the transmutation**
- **Provide a fast-spectrum irradiation facility** for material & fuel developments

Features:

- 50-100 MWth power
- k_{eff} around 0.95
- 600 MeV, 2.5 mA proton beam
- Highly-enriched MOX fuel
- Pb-Bi Eutectic coolant & target

2. EFIT (Industrial Transmuter)

Goals:

- Maximise the transmutation efficiency
- Easiness of operation and maintenance
- High level of availability for a cost-effective transmutation

Features:

- Several 100 MWth power
- k_{eff} around 0.97
- 800 MeV, 20 mA proton beam
- Minor Actinide fuel
- Pb coolant & target (gas as back-up solution)

Proton beam specifications

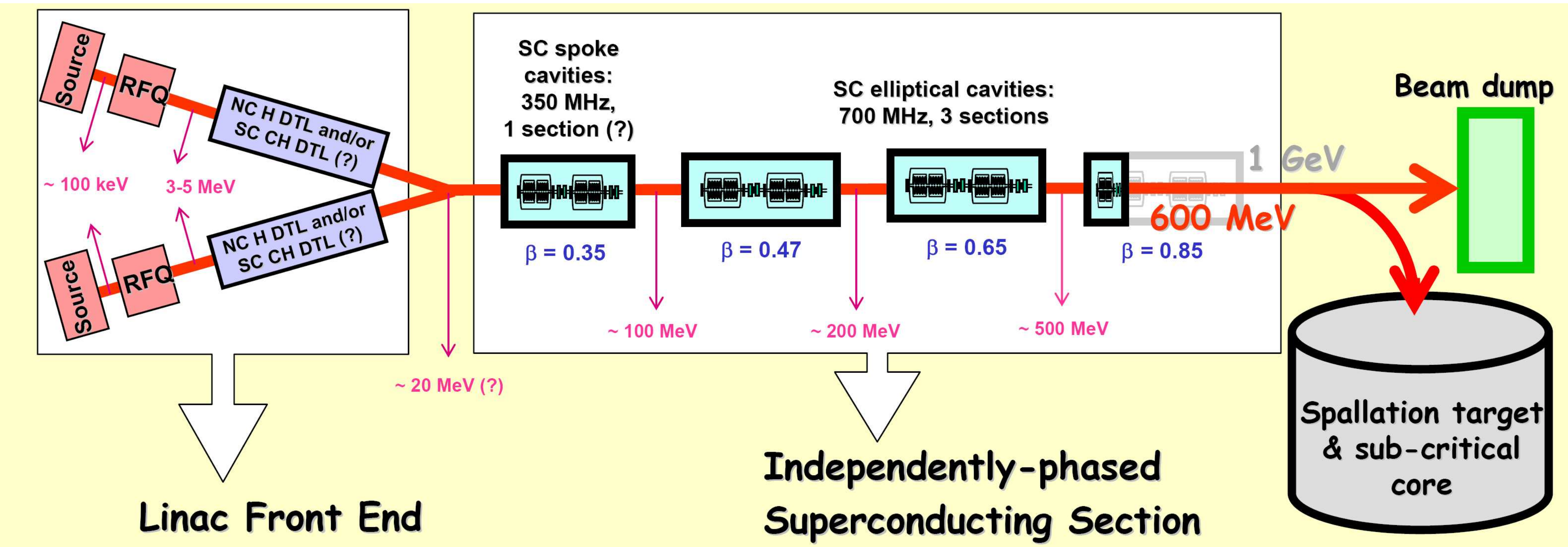
Table 1 – XT-ADS and EFIT proton beam general specifications

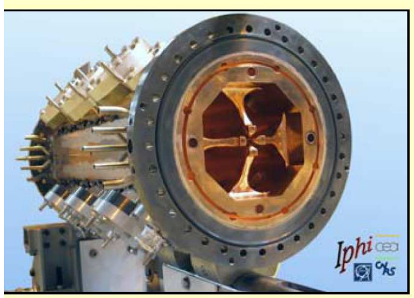
	XT-ADS	EFIT
Maximum beam intensity	2.5 – 4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertically from above	
Beam trip number	< 20 per year (exceeding 1 second)	< 3 per year (exceeding 1 second)
Beam stability	Energy: ± 1 %, Intensity: ± 2 %, Size: ± 10 %	
Beam footprint on target	Circular ∅ 5 to 10 cm, “donut-shaped”	An area of up to 100 cm² must be “paint-able” with any arbitrary selectable intensity profile
Beam time structure	CW, with 200 μs zero-current holes every 10^{-3} to 1 Hz, + pulsed mode capability (repetition rate around 50 Hz)	

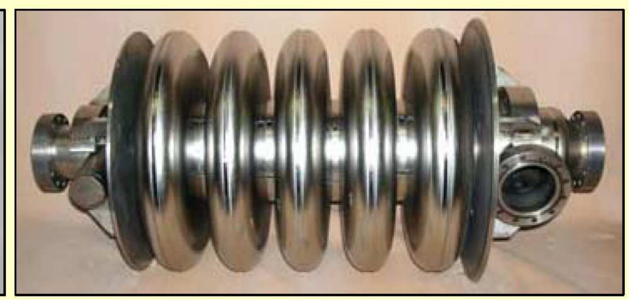
ADS linac reference scheme

SUPERCONDUCTING LINAC

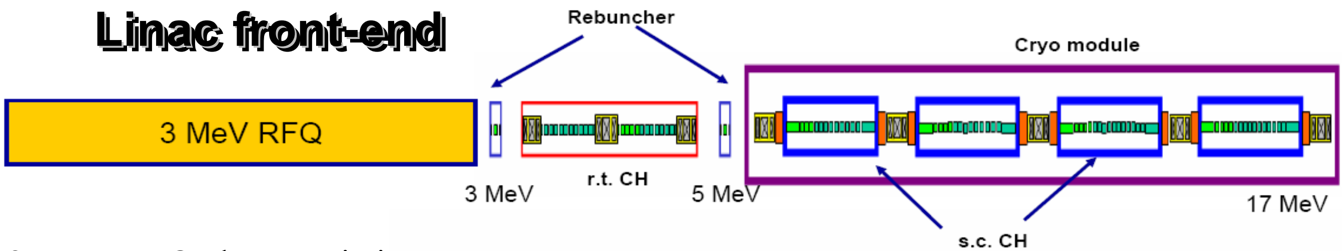
Highly modular and upgradeable; Excellent potential for reliability ; Very good efficiency







Linac front-end



352 MHz RFQ characteristics

Parameters	Values
Beam Current [mA]	30
Frequency [MHz]	352
Input Energy [keV]	50
Output Energy [MeV]	3.0
Inter-Electrode Voltage [kV]	65
Kilpatrick Factor	1.69
$\varepsilon_{in}^{trans., n., rms}$ [π mm-mrad]	0.20
Output Synchronous Phase [°]	-28.8
Minimum Aperture [cm]	0.23
Maximum Modulation	1.79
$\varepsilon_{out}^{x., n., rms}$ [π mm-mrad]	0.21
$\varepsilon_{out}^{y., n., rms}$ [π mm-mrad]	0.20
$\varepsilon_{out}^{z, rms}$ [MeV-deg]	0.09
Electrode Length [cm]	431.8
Beam Transmission [%]	99.9

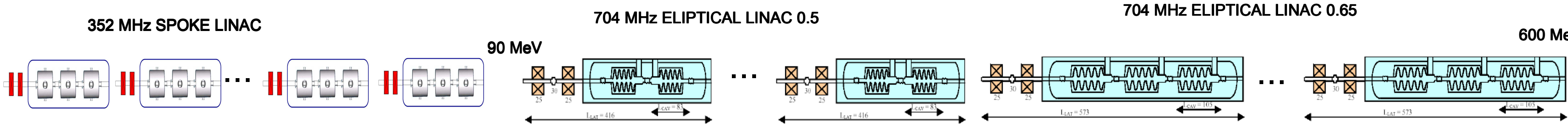
352 MHz DTL characteristics

Cavity	Gaps (φ_s [°])	Length [cm]	$W_{s,out}$ [MeV]	Eacc* [MV/m]
Rebuncher I	2 (-90°)	~7	3.0	2.79
RT-CH	11 (0°) 4 (-40°) 8 (0°)	~160	5.2	2.72
Rebuncher II	2 (-90°)	~7	5.2	5.11
SC-CH I	3 (-40°) 10 (0°)	~90	7.5	3.99
SC-CH II	4 (-40°) 10 (0°)	~105	10.4	3.97
SC-CH III	4 (-40°) 12 (0°)	~130	14.3	3.98
SC-CH IV	4 (-40°) 12 (0°)	~145	18.3	3.96

* Eacc: active acceleration gradient.

- Classical 4-vane RFQ with moderated Kp
- DTL booster using CH structures (KONUS beam dyn.)
- 17 MeV gained in less than 15 metres

Superconducting linac



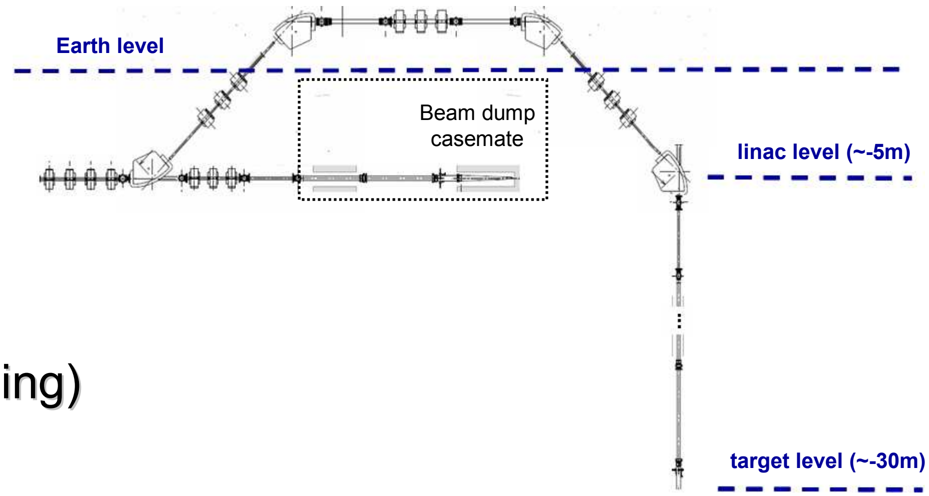
Section number	1	2	3	4
Input Energy [MeV]	17	90	190	450
Output Energy [MeV]	90	190	450	610
Cavity Technology	Spoke 352 MHz	Elliptical 704 MHz		
Structure β	0.35	0.47	0.65	0.85
Number of cavity cells	2	5	5	6
Number of cavities	60	30	42	16
Focusing type	NC quadrupole doublet			
Cavities/Lattice	3	2	3	4
Synch Phase [deg]	-40 to -18	-36 to -15		
Lattice length [m]	2.5	4.1	5.7	8.4
Section Length [m]	50	61	80	34
<gradient> [MeV/m]	1.4	1.6	3.4	4.7

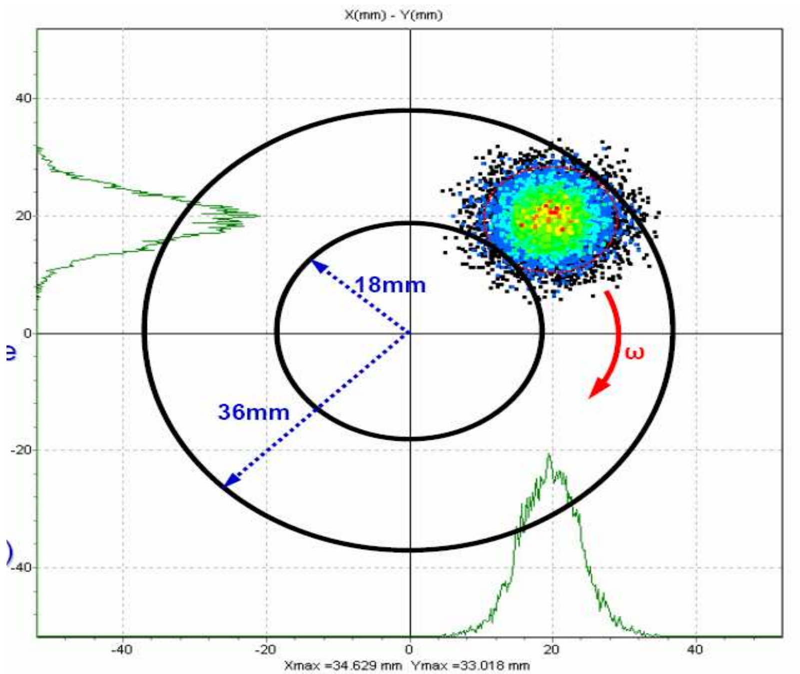
- Modular, independently-phased accelerating structures
- Moderate gradients (50mT B_{pk}, 25MV/m E_{pk}) & energy gain per cavity
- Overall length: about 225 metres

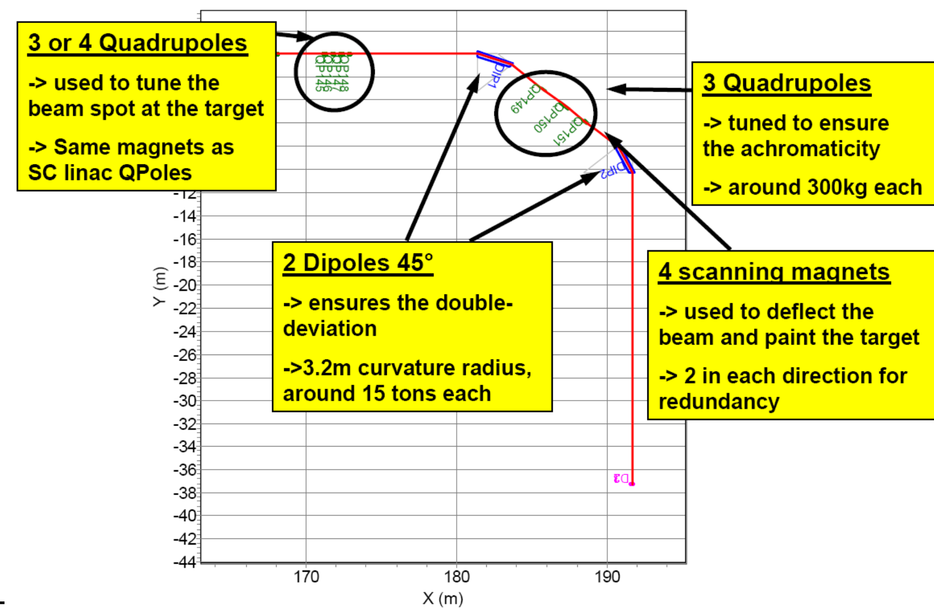
Final beam line to reactor

- Final beam line guarantees the position of the beam spot and ensures that only particles of nominal energy are delivered (doubly-achromatic lines)

- Also guarantees the required “donut-shape” distribution at the target (redundant beam scanning)







Advanced reference design : Beam Dynamics

... with assessed start-to-end beam dynamics

- Linac Tuning: using non destructive on line beam diagnostics
- Reliability: fault scenarios
- Beam losses (< 1 W/m)

Code package crucial capabilities

✓ « Close to real » beam tuning procedures using simulated diagnostics

✓ Use of 3D field maps for most of the elements (focusing magnets, RF cavities), high-order aberrations taken into account for the others (dipoles)

✓ Possibility to perform statistical error studies

Main Reliability Requirement: Beam Trips

Very low number of trips (< 1 sec)

- to avoid thermal stresses & fatigue on the ADS target, fuel & assembly
- to provide good availability.

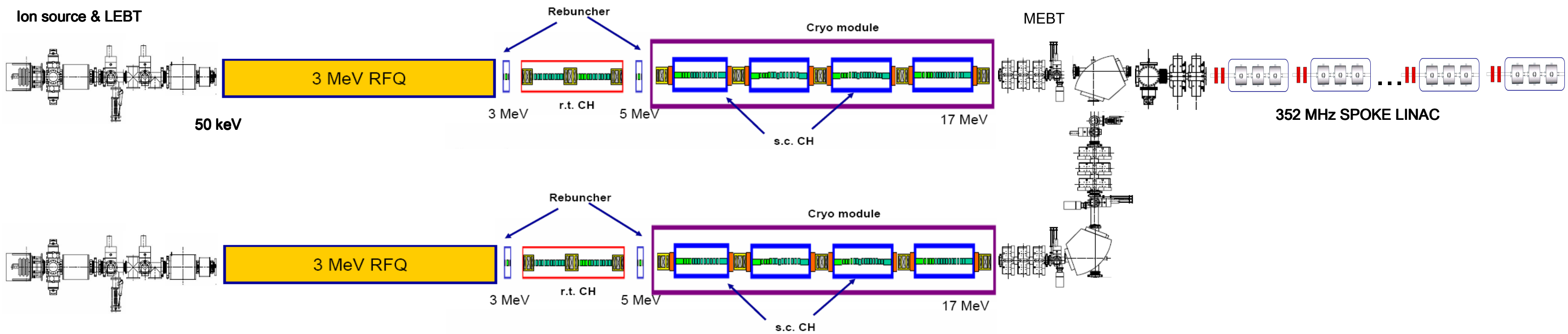
- **SPECIFICATION : less than N per operation cycle (3 months - 1 month stop)**

  (N ~ 5 for MYRRHA / XT-ADS)

Major guidelines to improve reliability:

1. Strong component design ("**overdesign**", "derating")
2. Inclusion of **redundancies** in critical areas
3. Enhance the capability of **fault-tolerant** operation

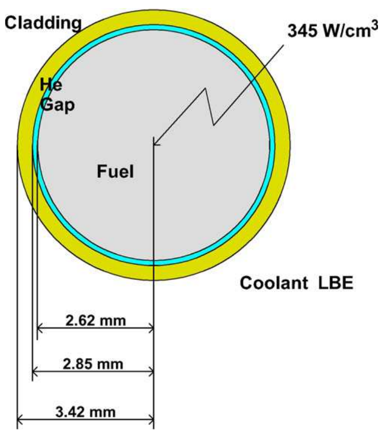
Front end : Redundancy

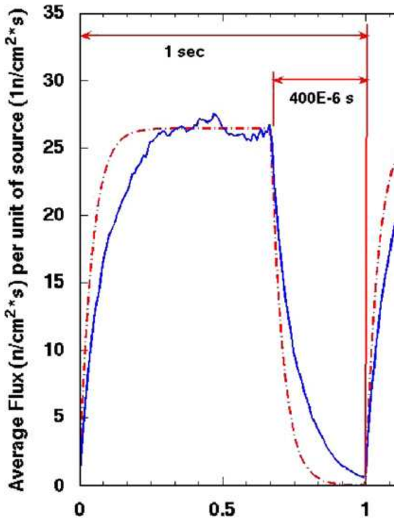


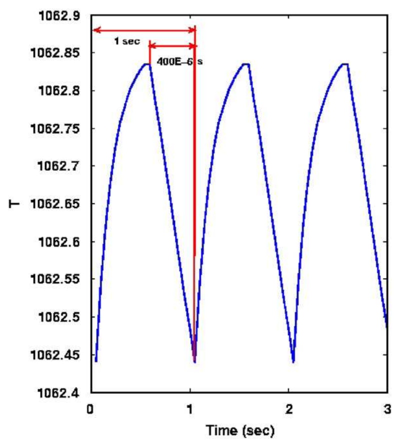
Strong Component Design (derating)

- SRF cavities Accelerating Gradients: important margins
- RF power amplifiers: important margins
- Couplers, tuners: robust design
- RF control electronics: robust design

Beam trip Thermal Transient Calculations







Slope:

~ 1 K in 1 ms

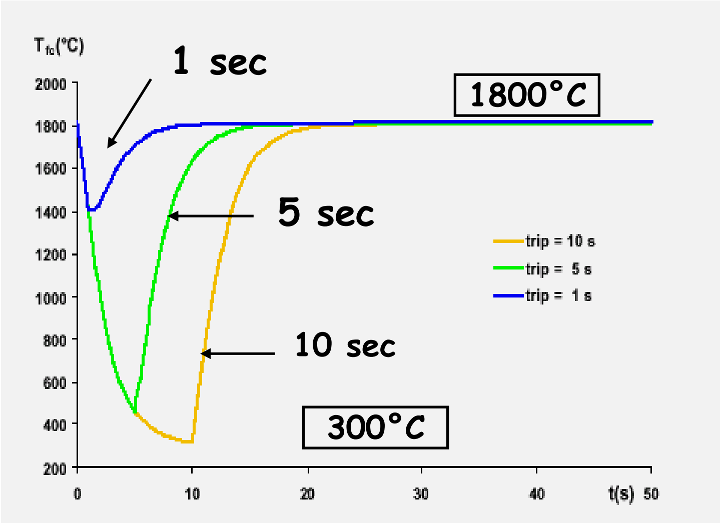


Figure 6-81: transient P-10 / central fuel temperature at midplane

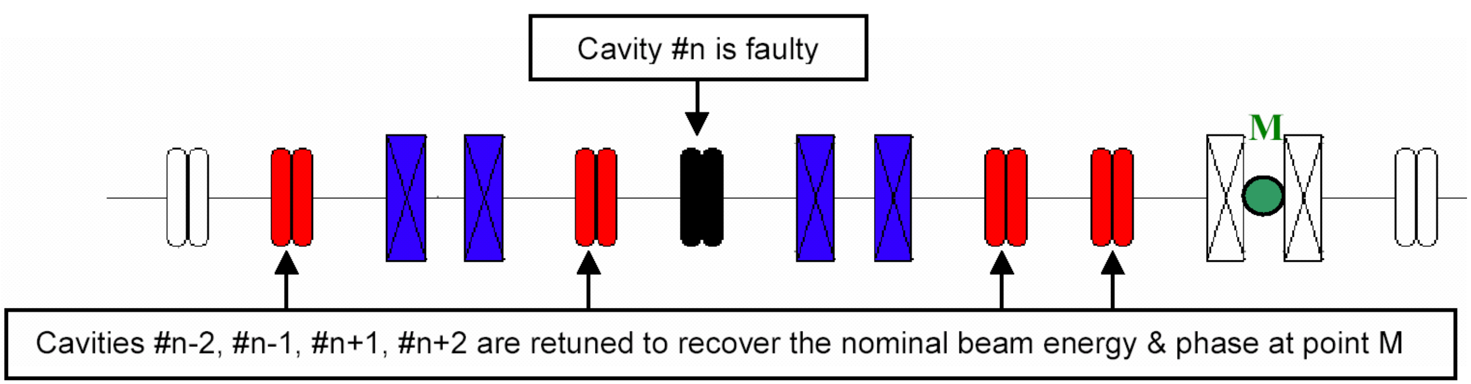
Fast fault-recovery scenario

retuning should be performed in less than 1 second in the case of a failure event

➲ Definition of a reference "fast fault-recovery scenario"

< 1 sec

- **detect (or anticipate) the RF fault** (via dedicated diagnostics & interlocks) & trigger beam shut-down
- **update the new LLRF field and phase set-points** of the correcting cavities (data have been determined & stored in FPGAs during commissioning)
- **detune the failed cavity** (w/ piezo-actuators) and switch off the failed RF loop
- **trigger beam re-injection** once steady state is reached



Classical Linac reliability analysis

GOAL of the ANALYSIS

- Estimate the number of malfunctions of the XT-ADS accelerator that cause a beam/plant shutdown, per period of operation (3 months = 2190 hours)
- Analyse the influence of MTBFs (Mean Time Between Failures), MTTRs (Mean Time to Repair), and of the degree of redundancy & fault-tolerance on the results
- Goal MTBF: better than 500 hours

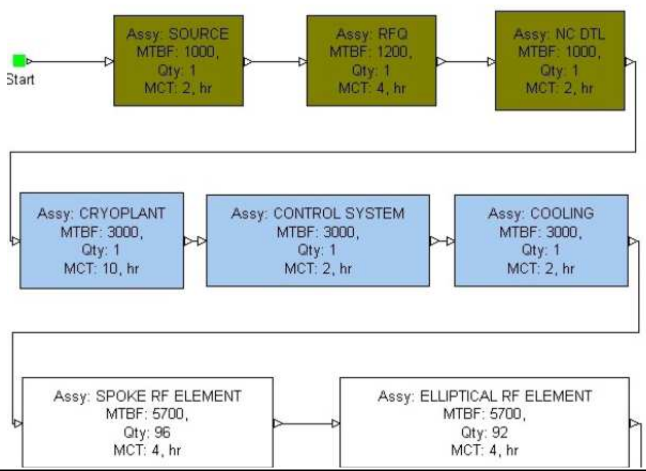
Linac reliability analysis

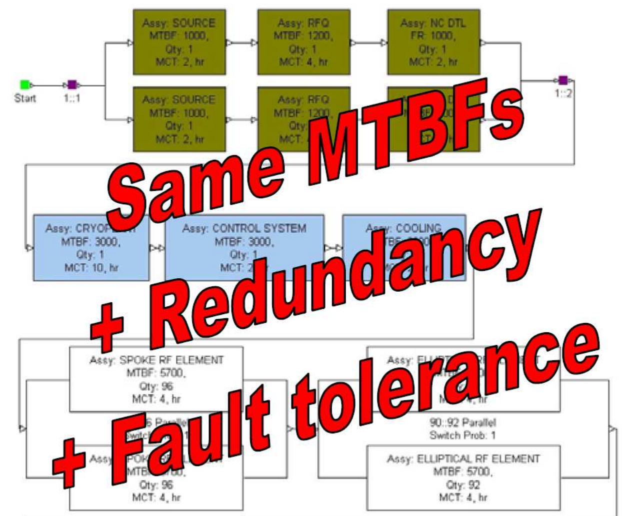
CLASSICAL LINAC DESIGN

- "all-series" (simplified) components
- every component failure leads to a global system failure
- poor MTBF, mostly due to the ~150 RF units

RELIABILITY-ORIENTED DESIGN

- same components MTBFs
- duplicated injector with fast switching magnet
- fault-tolerance in the SC linac





System MTBF	31.19 hours
Number of failures	70.23
Steady State Availability	86.6 %

System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

Code	Component	MTBF (h)	MTTR (h)	Source see source table)
EE	Extraction electrode	100000	10	3
RQ	RFQ	1200	10	1
CI	Circulator	50000	10	6
KL	RF source	10000	10	4, 2
HV	HVPS	4500	10	HYPOTHESIS
LL	LLRF	1.00E+05	10	1, 4, 4, 6
TR	Transmitter	5000	10	6
IM	Water-cooled magnet	1000000	10	5
PS	Magnets Power Supply	8000	10	2
WC	Cooling system (water)	4500	10	HYPOTHESIS
BV	Vacuum pump (any type)	20000	10	2, 3
WI	RF window	100000	10	6
FU	Serious leak in vacuum system	8000	10	HYPOTHESIS

	Project	Document	Denomination	Link
1	Miscellaneous	Eurotrans Deliverable 63	Table 4-4 – Reliability characteristics of the components used for the RBD analysis.	
2	Los Alamos Neutron Science Center (LANSCE)	Eurotrans Deliverable 57	Table 4: Results of reliability studies at LANSCE.	
3	International Fusion Materials Irradiation Facility (IFMIF)	IFMIF CDA Final Report	IFMIF CDA Final Report	http://www.frascati.enea.it/cda/FinalReport/sec2_6-15.html
4	US Department of Energy	ORNL/TM-2000/93	Computation of Normal Conducting and Superconducting linear Accelerator Facilities	http://www.ornl.gov/~webworks/cpr/rpt/108020_.pdf
5	International Linear Collider (ILC)	SLAC-PUB-12606	Availability and reliability for ILC	http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-12606.pdf
6	Spallation Neutron Source (SNS)	2001 Particle Accelerator Conference, Chicago	An Availability Model for the SNS Linac RF System	

MTBF results

without cryogenic systems

Conclusions:

• Reliability: need of more calculations and experimental results on thermal stress and fatigue of reactor components

• design optimisation (cost reductions if some risks are acceptable)

• additional specifications for beam power ramping up/down (after beam trips)

• more specifications on interfaces between accelerator beam systems and ADS core (safety aspects)

• develop the study, prototyping and test of all electronics and computing systems playing a role in fault handling, in order to allow fault-tolerance